COMPARISON OF AGRICULTURAL STAKEHOLDER SURVEY RESULTS AND DROUGHT MONITORING DATASETS DURING THE 2016 U.S. NORTHERN PLAINS FLASH DROUGHT

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Abstract

The evolution of a flash drought event, characterized by a period of rapid drought intensification, is assessed using standard drought monitoring datasets and on-the-ground reports obtained via a written survey of agricultural stakeholders after the flash drought occurred. The flash drought impacted agricultural production across a 5-state region centered on the Black Hills of South Dakota during the summer of 2016. The survey asked producers to estimate when certain drought impacts, ranging from decreased soil moisture to plant stress and diminished water resources, first occurred on their land. The geographic distribution and timing of the survey responses were compared to the U.S. Drought Monitor and to datasets depicting anomalies in evapotranspiration, precipitation, and soil moisture. Overall, the survey responses showed that this event was a multi-faceted drought that caused a variety of impacts across the region. Comparisons of the survey reports to the drought monitoring datasets revealed that the topsoil moisture dataset provided the earliest warning of drought development, but at the expense of a high false alarm rate. Anomalies in evapotranspiration were closely aligned to the survey reports of plant stress and also provided a more focused depiction of where the worst drought conditions were located. This study provides evidence that qualitative reports of drought impacts obtained via written surveys provide valuable information that can be used to assess the accuracy of high-resolution drought monitoring datasets.

1. Introduction

The comprehensive monitoring of agricultural and ecological drought conditions during the growing season requires a suite of datasets that can capture different aspects of a drought event such as below normal precipitation, soil moisture, and evapotranspiration (ET); increased evaporative demand; and associated deteriorations in vegetation health. In recent years, the proliferation of drought and vegetation indices derived from satellite remote sensing observations has promoted the routine monitoring of various biophysical and biological indicators of vegetation health such as plant vigor, leaf area index, gross primary productivity, ET, and solar-induced chlorophyll fluorescence (e.g., Tucker 1979; Liu and Kogan 1996; Huete et al. 2002; Myneni et al. 2002; Heinsch et al. 2003; Anderson et al. 2007a; Mu et al. 2011; Guanter et al. 2014, among others). In addition, observations from microwave sensors onboard polar-orbiting satellites such as the Soil Moisture Ocean Salinity (Kerr et al. 2012) and Soil Moisture Active Passive (Entekhabi et al. 2010) are used to estimate the near surface soil moisture content (0-5 cm) over the entire globe, albeit with much coarser horizontal resolution (~30-50 km) than vegetation datasets derived using visible and infrared satellite imagery. Recent advancements in land surface modeling and data assimilation have also led to the development of datasets that depict soil moisture content over multiple soil layers that include most if not all of the vegetation root zone (Rodell, et al. 2004; Xia, et al. 2012a). For drought monitoring purposes, key features of useful datasets are that they are updated on a regular basis and are available on a grid that provides continuous coverage over large geographic domains with horizontal resolutions sufficient to capture local and regional differences in drought severity.

Though spatially continuous soil moisture and vegetation condition datasets are a critical component of drought monitoring, a notable challenge is the difficulty assessing their accuracy over large regions given the lack of in situ observations with similar spatial resolutions. Precipitation and near surface air temperature observations are perhaps the easiest to obtain given the relative ease with which these measurements can be made. Inferences can then be made regarding soil moisture status and vegetation health at those locations based on long-term climatology. In situ soil moisture observations are available from soil moisture monitoring networks and climate reference stations across the U.S. and elsewhere around the world. Their resolution varies greatly across the U.S., with some states having relatively dense spatial coverage (at least one station per county), whereas other states only have a few stations. Harmonization of these records is also necessary to account for differences in the soil moisture sensors and quality control methods used by each network (Quiring et al. 2016). Information regarding vegetation biomass production and other properties can be obtained via direct measurement methods such as harvesting or indirect methods that use more easily observed quantities such as vegetation height to estimate the total plant biomass (Bonham 1989). Direct measurements of ET, which is an important indicator of vegetation health, can be obtained during field projects or via flux tower networks such as AmeriFlux and FLUXNET (Baldocchi et al. 2001).

In situ observations are generally preferred when assessing the ability of modeled and satellite-derived datasets to accurately depict soil moisture and vegetation conditions; however, it can be beneficial to use qualitative or “crowd-sourced” information when possible to augment these quantitative comparisons. Ground-level reports from trained observers and citizen scientists help fill in gaps in conventional observing networks and also potentially reduce representativeness errors because these reports integrate information over a larger area (field-scale to county level) rather than being valid only for a single point. This can be advantageous when assessing the accuracy of gridded datasets because the resolutions of the observations and the datasets are more consistent. When used individually, ground-level reports may have limited utility because of uncertainty in the quality and specificity of the observation and the objectivity of the reporter; however, in aggregate, they provide a useful snapshot of the current conditions over larger regions. For example, Otkin et al. (2013, 2016) showed that county-level crop condition and soil moisture reports compiled by the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service using input from local experts knowledgeable in visually identifying crop and soil moisture conditions provide valuable information about drought impacts on agriculture. Another useful resource is the Drought Impact Reporter (DIR; Smith et al. 2014). The DIR is an interactive web-based mapping tool where people can upload pictures and text describing drought conditions and impacts either locally or over larger regions. It is a passive information gathering mechanism because contributors need to be aware of the webpage and are in charge of submitting the pictures and text descriptions themselves.

To obtain more detailed information regarding the accuracy and utility of drought monitoring and climate resources, researchers can also directly engage with stakeholders via focus group meetings and interviews (e.g., Otkin et al. 2015b; McNeely et al. 2016) or by administering surveys that include questions tailored to a specific stakeholder group (Prokopy et al. 2017). In this paper, we assess the ability of several drought monitoring datasets to realistically depict the evolution of a flash drought event that occurred across the northern U.S. High Plains in 2016 using results from a detailed survey administered to agricultural stakeholders in the region after the event. A second objective is to evaluate the representativeness of the survey reports through a convergence-of-evidence approach with the drought monitoring datasets. The survey asked respondents to estimate when certain events, such as decreased topsoil moisture and plant stress, initially occurred on their land. Responses to this question serve as the basis for the evaluations presented in Section 4. The flash drought event (Otkin et al. 2018) that is the focus of this study developed very rapidly during June and affected parts of five states centered on the Black Hills of South Dakota. This region experienced a variety of impacts such as forest and grassland fires, lower grain yields, reduced forage production, and water quality and quantity issues that caused ranchers to reduce the size of their livestock herds and contributed to large economic losses across the region (NOAA, 2016). The paper is organized as follows. The survey methodology is discussed in Section 2 along with a description of the drought monitoring datasets evaluated during this study. A broad overview of the survey results is provided in Section 3, with detailed comparisons of the survey results and drought monitoring datasets presented in Section 4. Conclusions and discussion are presented in Section 5.

2. Datasets and Methodology

2.1. Survey of Agricultural Stakeholders

Funding from the National Integrated Drought Information System (NIDIS) and the National Oceanic and Atmospheric Administration (NOAA) was used to conduct a survey of agricultural producers impacted by the 2016 flash drought event in the northern U.S. High Plains. The survey included a set of questions that focused on the timing and severity of drought impacts experienced by the producers, the management actions taken in response to the drought, the types of drought monitoring information that were used when making management decisions, and the factors that affect the producer's ability to prepare for and adapt to drought conditions. It was developed with expert input and pretested by agricultural extension personnel in the drought-affected areas. The survey was sent to 2389 producers living in 42 South Dakota counties, 16 Wyoming counties, 13 Nebraska counties, and 13 Montana counties that experienced at least abnormally dry conditions through July 2016 according to the U.S. Drought Monitor (USDM; Svoboda et al. 2002). A stratified random sample that over-sampled counties experiencing the most severe drought conditions and under-sampled the larger number of counties experiencing only abnormal dryness was used to ensure that a sufficient number of responses were received from areas experiencing each level of drought severity. The sample frame was a list of producers participating in Federal farm programs, obtained via a Freedom of Information Request submitted to the USDA Farm Services Agency.

The National Drought Mitigation Center (NDMC) administered the survey, with surveys mailed to the producers using the U.S. Postal Service. Following the Dillman et al. (2009) protocol, a pre-survey letter was mailed to each producer in early November 2016, followed by the initial survey mailing in late November 2016 and a follow-up survey mailing in early January 2017. Of the 2389 surveys that were mailed, 516 (22%) were completed and returned to the NDMC of which 348 were received from agricultural producers. Surveys completed by absentee landowners who were not actively engaged in agricultural production were not included in the analysis. The respondent's zip code was used to represent the location of a given report; however, it should be noted that their responses could potentially integrate information from surrounding areas if they had land in more than one zip code. Figure 1 shows the locations for each of the 136 zip codes for which surveys were received from agricultural producers. There is almost complete coverage over western South Dakota, northeastern Wyoming, and southeastern Montana where drought conditions were most severe. This area will hereafter be referred to as the core drought region (CDR; see Fig. 1). There are also numerous reports surrounding the Big Horn Mountains in south-central Montana, and extending to the east and south of the CDR across central and eastern South Dakota and northwestern Nebraska where drought conditions were less severe.

Survey data is subject to sampling and non-sampling errors (Dillman 1991). Paper questionnaires rely on the ability of the respondents to accurately understand the meaning of each question and to provide accurate answers to those questions (Redline and Dillman 2002). Our analysis assumes that the respondents noticed if a given condition occurred on their land (see Table 1 for the list of conditions) and were able to accurately remember the date when they first observed that condition. Potential error sources include failure to notice a given condition and inaccurate recollection of when that condition was initially observed. In preparing the datasets for analysis, the decision was made to group records into 2-week intervals to account for this type of measurement error. Whereas individual respondents may be unable to remember the exact date that each condition occurred, their approximations can still provide enough information to evaluate the spatial coherence of the reports and to establish trends in the drought impacts. In light of these considerations, the objective of this study is not only to use the survey reports to assess the accuracy of the drought monitoring datasets, but also to use a convergence-of-evidence approach to assess the representativeness and accuracy of the survey reports themselves.

2.2. Evaporative Stress Index

The Evaporative Stress Index (ESI) depicts standardized anomalies in the ratio of actual to reference ET, where the actual ET flux is estimated from remote sensing data using the Atmosphere Land Exchange Inverse (ALEXI; Anderson et al. 1997, 2007a,b, 2011) surface energy balance model and the reference ET flux is computed using a Penman-Monteith formulation for a grass reference surface (Allen et al. 1998). Normalization of actual ET by a reference ET flux serves to limit the role of non-moisture related drivers of ET (e.g., solar radiation and atmospheric demand), thus leading to a more useful depiction of moisture-related stress in vegetation. Due to its foundation on diagnostic retrievals of ET, the ESI conveys useful information about vegetation health and soil moisture availability.

ALEXI uses land surface temperatures retrieved from satellite thermal infrared imagery and the Norman et al. (1995) two-source energy balance model to compute latent, sensible, and ground heat fluxes for vegetated and soil components of the land surface. The total surface energy budget for each satellite pixel is computed using the observed rise in land surface temperatures during the morning. Because ET estimates can only be computed for satellite pixels that remain clear during the morning, it is necessary to composite the clear-sky ET estimates over longer multi-week time periods to achieve more complete domain coverage. For this study, we chose to compute the ESI using a 4-

week compositing period because it provides a compromise between the fast response of a shorter 2-week ESI composite to rapidly changing conditions and the complete domain coverage provided by longer composite periods (Otkin et al. 2013). The ALEXI model is run daily over the contiguous U.S. with 4-km horizontal grid spacing, with 4-week ESI anomalies computed at weekly intervals for each grid point in the domain using data from 2001-2017. The reader is referred to Anderson et al. (2007a, 2013) for a more complete description of the ALEXI model and the ESI.

2.3. North American Land Data Assimilation System

Gridded soil moisture analyses were obtained from the North American Land Data Assimilation system at 0.125° resolution (Xia, et al. 2012a,b) and then interpolated to the ESI grid. In particular, hourly data were acquired from three land surface models, including the Noah (Ek et al. 2003; Barlage et al. 2010; Wei et al. 2013), Variable Infiltration Capacity (Liang et al. 1996), and Mosaic (Koster and Suarez 1996) models. Each of these land surface models simulates changes in soil moisture content at different soil depths using energy and water balance equations. Different approximations for key processes in each model mean that the soil moisture response often varies between models for the same atmospheric forcing. Xia et al. (2014) has shown that the ensemble mean of these models provides a more accurate representation of soil moisture conditions than do the individual models. As such, ensemble mean analyses are used during this study. Topsoil (0-10 cm) and total column (0-2 m) soil moisture content from the ensemble mean was averaged over 4-week periods and then standardized anomalies were computed at weekly intervals for each soil layer (hereafter referred to as TS and TC, respectively) using data from 1979-2017.

2.4. Temperature and precipitation

Near surface air temperature anomalies preceding and during the drought event were computed using analyses from the Climate Forecasting System Reanalysis (CFSR), which is a fully coupled land-ocean-atmosphere modeling system (Saha et al. 2010). CFSR data are available every 6 h on an ~38 km resolution grid. The 2-m temperature (T2M) field is estimated in the CFSR by vertically interpolating between the surface skin temperature and the air temperature on the lowest model level. For this study, the daily average T2M was computed at each grid point and then standardized anomalies for the mean T2M over a 4-week period were computed at weekly intervals using data from 1979-2017. In addition, precipitation analyses on a 0.25° resolution grid were obtained from the Climate Prediction Center, generated using daily precipitation reports from National Weather Service stations and cooperative observers (Higgins et al. 2000). Daily analyses were accumulated over 4-week periods from 1948-2017 and then 4-week Standardized Precipitation Index (SPI; McKee et al. 1993) anomalies were computed at weekly intervals. The SPI is widely used to monitor meteorological drought conditions (Hayes et al. 2011) and when combined with T2M anomalies provides greater context for the atmospheric forcing during this event.

2.5. United States Drought Monitor

The USDM has become the gold standard for drought monitoring in recent years because it combines information from multiple data sources into a single analysis (Svoboda et al. 2002). A team of experts considers various inputs such as precipitation and soil moisture deficits, crop and range conditions, surface stream flow departures, various drought metrics, and local impact reports to determine the best estimate of drought severity each week. Though this process is designed to be objective, it is important to note that there is uncertainty in the analyses because not all of the inputs will indicate the same drought severity each week. The USDM analyses depict abnormally dry conditions (D0) and four drought categories including moderate (D1), severe (D2), extreme (D3), and exceptional (D4) drought. Its accuracy depicting conditions during this flash drought event are assessed using the survey reports and drought monitoring datasets described in this section.

3. Survey results

The producer survey described in Section 2.1 included a set of questions covering a diverse range of topics that together promote a more nuanced understanding of their decision making process and the impacts of the drought on both natural and managed ecosystems. A detailed synopsis of the survey results is provided in Haigh et al. (2018). Here, we provide an overview of their responses to a question that focused on observed impacts. In particular, this question asked the respondents to indicate whether a certain condition such as plant stress or decreased topsoil moisture occurred on their land and, if so, to estimate the date upon which it first occurred during 2016. Table 1 provides a descriptive summary of their responses for a set of 14 conditions. The table includes the number of responses for each condition, along with the percentage of respondents that indicated that a given condition did or did not occur on their land, and the date of first occurrence averaged over all of the affirmative (YES) responses. Questions A and B refer to changes in soil moisture content, questions C-I to vegetation impacts, and questions J and K to diminished water resources. The last two questions (L and M) refer to the occurrence of fires and insect infestations.

Overall, the results indicate that most producers observed decreases in topsoil and subsoil moisture content (94% and 90%, respectively) during 2016. Most producers also observed vegetation stress in their crops or pasture (92%) along with deteriorating range conditions (86%) and decreased forage productivity (86%). Fewer respondents noted that plant emergence was delayed or absent (65%), while approximately half (51%) observed plant death in their crops or pasture. Only 39% of the producers observed poor grain fill in their crops; however, this low percentage is misleading because this question was only applicable to 54% of the respondents. If this is taken into account, nearly 70% of the respondents with crops noted poor grain fill during 2016. In regard to water resources, most producers noted lowered water levels or a lack of water in ponds, streams, and other water sources (80% and 70%, respectively). About a sixth of the respondents stated that their wells were unable to keep up with their livestock or irrigation needs, while similar percentages also observed fires and infestations of insects or other pests in their area. In summary, these reports show that this was a multi-faceted drought that strongly impacted soil moisture, vegetation health, and the local hydrology. Inspection of the mean dates in the last column also reveal a logical sequence of events, with decreases in soil moisture or delayed plant emergence and growth occurring in May followed by deteriorations in plant health and productivity and decreasing water levels during June. Even though the mean occurrence dates obscure local differences in the timing of drought intensification (see Section 4), their logical progression provides confidence in the veracity of these reports. As such, the survey results provide a useful case study with which to assess the accuracy of drought monitoring datasets during a high impact flash drought event.

4. Flash drought overview and dataset comparisons

In this section, we examine the spatial and temporal evolution of the flash drought and its associated impacts on soil moisture, vegetation health, and water levels through detailed comparisons of the survey results with several datasets used to monitor drought conditions. To make this assessment more tractable, the drought monitoring datasets are compared to only three of the questions listed in Table 1; namely, questions A, E, and J (hereafter referred to as QA, QE, and QJ). These questions were chosen to represent the impact of the drought on soil moisture (QA), vegetation health (QE), and water levels (QJ). The drought overview in this section will proceed at monthly intervals from the end of March to the end of August, thereby covering the onset and intensification stages of the drought. This is appropriate given that the survey questions focused on when each of the conditions were initially observed. For each figure, the geographical region covered by a zip code in which a certain condition was observed is indicated by blue hatching if it occurred during that month and by black hatching if it occurred prior to that month. The survey results are compared to the USDM and to ESI, SPI, TC, TS, and T2M anomalies computed over a 4-week time period valid at the end of each month. Note that the color bar is reversed for the T2M anomalies so that positive anomalies indicative of enhanced drying are shown in red and brown colors similar to the other datasets. The analysis is novel in that we assess the congruence between different drought monitoring datasets and actual observations of drought impacts from on-the-ground observers.

4.1. March 2016 drought conditions

At the end of March (Fig. 2), an extensive area of abnormally dry conditions (D0) with several pockets of moderate (D1) to severe (D2) drought conditions extended from Wyoming northeastward across parts of Montana and South Dakota and most of North Dakota according to the USDM (Fig. 2a-c). This large area of dryness had developed in response to a prolonged period of warmer than normal temperatures and near to below normal precipitation during the preceding fall and winter. Slightly wetter conditions had returned to parts of the region during March (Fig. 2g), most notably across Wyoming and parts of surrounding states. Much drier conditions, however, persisted across far eastern Montana and the western half of North Dakota. Unfortunately, any benefits derived from the brief respite from the unusually dry conditions of the preceding months were offset by warmer than normal temperatures (Fig. 2h) and an associated lack of snow cover that led to elevated evaporation rates and a continued drawdown of soil moisture content. This is consistent with the scattered reports of decreased TS moisture content (Fig. 2a) and lowered water levels (Fig. 2c) across the region, with the largest concentration of reports located in the CDR. The locations of these reports also align well with areas of abnormal dryness depicted by the ESI (Fig. 2d), to a lesser extent with the NLDAS TS moisture anomalies (Fig. 2e). In contrast, all of the lowered water level reports and most of the decreased topsoil moisture reports are located in areas with positive NLDAS TC soil moisture anomalies (Fig. 2f). This disagreement, combined with the warmer and drier than normal conditions of the previous months, suggests that the land surface models may have been unable to properly simulate the drawdown in subsoil moisture content during the cool season. Additional studies are necessary to determine if this is representative of the long-term model behavior in the region or if it is peculiar to this particular event.

4.2. April 2016 drought conditions

By the end of April (Fig. 3), abundant precipitation (Fig. 3g) combined with near normal temperatures (Fig. 3h) had eradicated the abnormally dry conditions across most of the region according to the USDM (Fig. 3a-c). The more favorable weather conditions led to enhanced ET rates as indicated by the positive ESI anomalies across the southern third of the region and over parts of South Dakota and western North Dakota (Fig. 3d). The heavier precipitation also greatly improved the NLDAS TS moisture depiction (Fig. 3e), but was insufficient to appreciably change the TC soil moisture (Fig. 3f). Further to the west, moderate-to-severe drought conditions persisted over the Big Horn Mountains of Wyoming and Montana in regions that missed the heavier precipitation and remained warmer than normal. Another region of below normal precipitation was located over the Black Hills of South Dakota and northeastern Wyoming. This area was characterized by large negative anomalies (< -1) in the ESI and NLDAS soil moisture datasets (Fig. 3d, e).

Inspection of the survey results shows that there were widespread new reports of decreased TS moisture across the CDR, most notably to the east of the Black Hills and over southeastern Montana (Fig. 3a). There were also some reports of plant stress and lowered water levels in this region (Fig. 3b, c). Most of these new reports were located in areas where the USDM did not depict drought or abnormally dry conditions at the end of April. All of the monitoring datasets (Fig. 3d-f) contain large negative anomalies (< -1) over the Black Hills and parts of northeastern Wyoming, which suggests that the drought depiction by the USDM should have been more severe in this region. Further to the north, however, many of the new reports of decreased topsoil moisture and lowered water levels were located where the NLDAS soil moisture datasets indicated conditions were near or better than normal. This discrepancy could point toward problems with the NLDAS soil moisture depiction, but it is also possible that it is a manifestation of the lingering affects of the warm and dry winter that preceded the more favorable conditions in April. It is also possible that the survey reports of new impacts may have lagged their actual onset because some stakeholders may have noted the decreasing soil moisture and water levels only when the vegetation began to green up in the spring. Even so, it is evident that most of the survey reports of increasing stress are concentrated over the CDR.

4.3. May 2016 drought conditions

By the end of May (Fig. 4), very dry conditions had returned to most of the CDR (Fig. 4g). The USDM analysis depicted a large expansion of abnormally dry conditions across the region, including the introduction of a small area of moderate drought over the western Black Hills (Fig. 4a-c). The area of drought expansion in the USDM is consistent with where the respondents indicated increasing drought stress during April, but does not extend as far to the north and east (Fig. 3a-c). Similar to April, many of the new survey reports of impacts were located outside of where the USDM was currently depicting dry conditions, indicating some delay in the USDM response to the changing conditions. A substantial number of new impact reports were received for each of the survey questions during May. New reports of decreased TS moisture were located primarily along the fringes of the area of abnormal dryness depicted by the USDM and also extended further to the east across South Dakota (Fig. 4a). Reports of plant stress and lowered water levels also increased greatly within the CDR (Fig. 4b, c), with most of the lowered water level reports located in the northern part of the CDR whereas the plant stress reports were more evenly distributed.

Comparison to the drought monitoring datasets shows that most of the new survey reports were located within an area of well below normal rainfall (Fig. 4g) and increasing NLDAS TS moisture deficits (Fig. 4e). In contrast, the ESI indicates that conditions were generally good across the CDR (Fig. 4d), with the best conditions located to the west and south of the CDR where the heaviest precipitation had occurred during the previous two months. Temperatures were also much cooler than normal during May, with several hard freezes (minimum T2M < 28° F) occurring across the region from 11-15 May. Though freezing temperatures during May are not unusual across this part of the U.S., the severity and persistence of the cold temperatures was unusual and together heavily damaged the vegetation in some locations. The freezing temperatures complicate interpretation of the survey results given its detrimental impact on the vegetation; however, the survey results and monitoring datasets generally indicate that conditions were deteriorating across the CDR by the end of May following the brief period of improving conditions in April.

4.4. June 2016 drought conditions

Flash drought conditions, characterized by a period of rapid drought intensification (Otkin et al. 2018), occurred across the CDR during June, with most areas experiencing at least a 2-category increase in drought severity during the previous month (Fig. 5). There was a large increase in the number of reports indicating worsening conditions across the CDR, with nearly complete coverage for all three survey questions by this time (Fig. 5a-c). Widespread reports of decreased TS moisture and scattered reports of plant stress and lowered water levels were also present over central and eastern South Dakota in locations that were not yet depicted as being in drought by the USDM. The period of rapid drought intensification was accompanied by the return of much warmer than normal temperatures (Fig. 5h) and the continuation of below normal precipitation in most locations (Fig. 5g). The rapid deterioration in vegetation health conditions is illustrated by the widespread appearance of large negative ESI anomalies across the CDR, including very large anomalies (< -1.5) over the Black Hills where the USDM was depicting severe-to-exceptional drought conditions (Fig. 5d). Unlike the surrounding plains where drought conditions were not as severe, the Black Hills had experienced large precipitation deficits during each of the previous three months and were clearly showing the cumulative impact of the hot and dry weather during June. In contrast, the NLDAS TS moisture anomalies indicate that dry conditions prevailed not only across the CDR but also across most of the northern Plains (Fig. 5e). Similar to previous months, the NLDAS TC soil moisture (Fig. 5f) exhibits a heterogeneous pattern of below and above normal conditions, with the geographic distribution of the anomalies closely resembling the precipitation pattern in the 6-month SPI (not shown). Though the TC soil moisture provides useful information about long-term drought conditions, the spatial details of this dataset differed markedly from those depicted by the USDM, survey reports, and other monitoring datasets at this stage of the drought.

When assessing the evolution of the drought conditions represented by the survey reports during the previous three months, it is evident that the plant stress and decreased TS moisture reports often preceded the appearance of abnormally dry (D0) and moderate drought (D1) conditions in the USDM by several weeks during the intensification stage of the drought. The analysis also reveals that the NLDAS TS moisture dataset provided the earliest warning of drought development, but that this came at the cost of a high false alarm rate. The area covered by large TS moisture deficits was often much larger than the area experiencing large vegetation impacts according to the ESI and plant stress reports. Though several prior studies (Otkin et al. 2013, 2014, 2015a) have shown that the ESI can provide early warning of drought onset, this did not occur during this particular event when using the ESI computed over a 4-week time period. The 2-week ESI product, however, did capture the rapidly worsening conditions more quickly and led the introduction of drought conditions in the USDM by 2-3 weeks (not shown). Compared to the SPI and NLDAS soil moisture datasets, the ESI anomalies align better with the plant stress reports and provide a more focused depiction of where the worst drought conditions were present at the end of June.

4.5. July 2016 drought conditions

The drought intensity peaked across the CDR by the middle of July, with a large area of severe-to-extreme drought conditions still depicted by the USDM at the end of the month (Fig. 6). According to the USDM, most of the region experienced either a 3- or 4-

category increase in drought severity during the previous two months. This rapid rate of intensification is consistent with the flash drought definition recommended by Otkin et al. (2018). The eastward extension of abnormally dry conditions across the southern two-thirds of South Dakota occurred where there were already many reports of decreased TS moisture and plant stress at the end of June that were then followed by numerous new reports during July (Fig. 6a, b). This provides further evidence that the impacts reported by the survey respondents preceded drought intensification in the USDM by up to several weeks, while also providing confirmation of the worsening conditions when changes were made to the USDM. By the end of July, the CDR was almost completely covered by decreased TS moisture and plant stress reports. Reports of low water levels were also very common within the CDR, but were sporadic elsewhere where drought conditions were less severe according to the USDM (Fig. 6c).

Conditions had stabilized across the CDR by the end of July due to the return of near normal temperatures across the entire region (Fig. 6h) and beneficial rainfall in some locations (Fig. 6g). The slightly more favorable conditions led to modest improvements in the ESI and NLDAS TS moisture anomalies (Fig. 6d, e); however, the NLDAS TC soil moisture analysis was mostly unchanged from the previous month (Fig. 6f). Areas with the largest TS moisture anomalies generally occurred where there were large negative 1-month SPI anomalies (Fig. 6g) due to the tight coupling between short-term precipitation departures and TS moisture anomalies. Though conditions had stabilized by the end of July within the CDR, they continued to worsen across much of central and eastern South Dakota and southward across eastern Wyoming and western Nebraska. This expansion of abnormally dry conditions had occurred in regions that had large rainfall deficits and were characterized by a rapid decrease in the ESI. The southwestward extent of this new area of drought cannot be verified using the survey reports because none were received in southern Wyoming (Fig. 1); however, a large increase in survey reports accompanied the eastward expansion across South Dakota.

4.6. August 2016 drought conditions

By the end of August (Fig. 7), conditions had finally started to improve across most of the CDR according to the USDM and each of the drought monitoring datasets. The largest improvements occurred in the NLDAS TS moisture dataset in response to the return of normal to above normal precipitation in many locations (Fig. 7g). The ESI also indicated that conditions had improved; however, the anomalies remained negative across most of the CDR (Fig. 7d). The negative ESI anomalies illustrate the longer-term impact of the severe drought on vegetation health. In many areas the plants were unable to respond fully to the improving soil moisture conditions, presumably because some plants had already died or gone into dormancy. There were very few new reports of decreased TS moisture or plant stress across the region (Fig. 7a, b); however, there were several new reports of lowered water levels across the eastern half of South Dakota where moderate drought had been present in July and abnormal dryness was still occurring in August according to the USDM.

4.7. Time series comparisons

In this section, we quantitatively assess the evolution of the drought monitoring datasets at weekly intervals preceding and following the dates upon which a respondent reported decreased TS moisture, vegetation stress, or decreased water levels. Figure 8 shows the evolution of the USDM, SPI, ESI, NLDAS TS, and NLDAS TC datasets averaged over all zip codes during a 12-week period centered on the date that the impact first occurred (week zero). Re-centering the time series for each zip code allows for a more consistent comparison of the datasets because it accounts for the different timing of drought impacts across the region. All grid points on the 4-km resolution grid located within each zip code were identified using a shape file and then used to compute the mean for each dataset and zip code. An average time series was then computed for each dataset and survey question using the re-centered time series from all respondents that indicated a certain condition occurred. The resultant time series are then used to evaluate the consistency between the timing of the reported impacts and the characteristics of the drought monitoring datasets.

Overall, inspection of each set of time series in Fig. 8 reveals a similar hierarchy, with the SPI and NLDAS TS moisture datasets having the largest negative anomalies at week 0, whereas the ESI was less severe and lagged the SPI and NLDAS TS moisture datasets by about 2 weeks on average. In contrast, the NLDAS TC soil moisture anomalies were less severe and even indicated that conditions were better than average when decreased TS moisture and plant stress first occurred (Figs. 8a, b). These results are consistent with those found in the qualitative assessments shown in previous sections. It is encouraging to note the internal consistency in each dataset where anomalies at week 0 generally become more negative and the USDM-depicted drought intensity more severe as the impacts of the flash drought progressed from decreased TS moisture (Fig. 8a) to plant stress (Fig. 8b), and finally to lower water levels (Fig. 8c). Inspection of the time series reveals that the datasets began to depict deteriorating conditions 2-3 weeks prior to reports of decreased TS moisture, 4-5 weeks prior to the onset of plant stress, and more than 6 weeks before lower water levels were noted. This behavior is consistent with the typical progression of a drought where only a short period of dry weather is necessary for TS moisture deficits to develop but a longer period is required for hydrological impacts to occur.

Finally, the magnitudes of the anomalies for each dataset are generally consistent with what would be expected to occur at the onset of each of these impacts. For example, the SPI and NLDAS TS moisture anomalies were approximately -0.25 – equivalent to the 40^{th} percentile of a normal distribution – when decreased TS moisture was initially noted (Fig. 8a). The average ESI anomaly was near zero when this particular impact occurred; however, it decreased to approximately -0.25 by the time respondents observed the onset of plant stress (Fig. 8b). Likewise, though the average NLDAS TC soil moisture anomaly was positive when both of these impacts occurred, it had become slightly negative by the time lower water levels had developed (Fig. 8c). Together, these results indicate that the qualitative reports on average are consistent with our expectations of drought evolution both in the timing of the associated impacts and in the magnitude of the anomalies in the monitoring dataset most closely related to a given impact. As such, this quantitative analysis provides increased confidence that qualitative reports such as those acquired during this study can accurately capture drought impacts.

5. Discussion and conclusions

This study examined the evolution of a flash drought event that severely impacted farmers and ranchers across a 5-state region centered on the Black Hills of South Dakota during the summer of 2016. A novel application of the study was its use of impact reports from agricultural stakeholders to evaluate the evolution of the flash drought event and to assess the ability of different drought monitoring datasets to accurately depict the timing of its onset and subsequent severity and spatial extent. The impact reports were obtained via a written survey administered to agricultural producers several months after the event. The timing and spatial distribution of the survey responses were compared to the USDM and to datasets depicting standardized anomalies in precipitation (SPI), ET (ESI), and soil moisture content (NLDAS TS and NLDAS TC, respectively).

Overall, the survey responses revealed that this was a multi-faceted drought event characterized by soil moisture deficits, plant stress, and lowered water levels in ponds, streams, and wells. Comparison to the USDM analyses showed that the producer reports of decreasing TS moisture and increasing plant stress often occurred several weeks prior to the appearance of abnormally dry conditions in the USDM both within the CDR and across other parts of the region. This delayed response of the USDM to rapidly changing conditions during flash drought events was also noted by Otkin et al. (2013, 2016). Even so, the spatial extent of the area containing abnormally dry conditions in the USDM was very similar to the spatial coverage of the survey responses after the drought reached its maximum severity. When comparing the drought monitoring datasets, it was evident that the NLDAS TS moisture dataset provided the earliest warning of drought development during May and June, but that this came at the expense of a high false alarm rate because most vegetation had deeper roots that could access total column moisture. Though the

ESI did not provide early warning during this particular event, its spatial extent was more closely aligned with the survey reports of plant stress than the other datasets and also provided a more focused depiction of where the worst drought conditions were occurring based on vegetation impacts.

Agriculture dominates the regional economy so accurate monitoring of vegetation health conditions is critical when determining drought impacts and severity. In general, there was reasonable agreement between the locations of the survey reports and areas that contained negative anomalies in the SPI, ESI, and NLDAS TS moisture datasets. Drought development during June was hastened by increased evaporative demand associated with above normal temperatures and near-surface water vapor pressure deficits, consistent with studies by Otkin et al. (2013) and Ford and Labosier (2017). This was illustrated by the rapid development of large negative ESI anomalies that indicated that moisture stress had rapidly increased across the CDR. Overall, the results illustrate the importance of using a variety of datasets to capture the evolution of a drought and the cascading impacts from elevated evaporative demand and below normal precipitation to decreasing TS moisture and deteriorating vegetation health conditions to below normal TC soil moisture and diminished surface water resources. Additional studies are necessary to explore these cascading effects in greater detail.

This study has shown that qualitative reports obtained via surveys administered to stakeholders after a drought event provide valuable information that can be used to assess the accuracy of drought monitoring datasets. As such, these ground-based observations of actual drought impacts complement information provided by in situ datasets that provide quantitative measurements but often have sparse spatial coverage that limit their use for verification purposes. Though the survey results presented in this study lack quantitative measurements of drought severity, inferences can still be made based on the geographic distribution of the various drought impacts. More extensive information could potentially be obtained via dedicated observers that provide pictures and descriptions of the impacts as they evolve during a drought event.

One potential approach would be to leverage the extensive volunteer observing capabilities developed through organizations such as the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS; Reges, 2016). A very important feature of large volunteer networks is that they can provide impact reports across a wide range of climate, soil, and vegetation types and are not limited to agricultural regions. Ideally, reports and pictures would be provided during both drought and non-drought years, and for all seasons, in order to place observed impacts into proper context. Despite their qualitative nature, reports from local observers provide tangible evidence of actual drought impacts and therefore should be used more extensively when assessing the accuracy of modeled and satellite-derived drought monitoring datasets. These reports complement quantitative observations provided by in situ soil moisture, ET and vegetation biomass measurement networks, which represent conditions only at discrete points and are typically sparsely distributed.

Finally, results obtained via surveys could also be complemented through focus group meetings with the affected stakeholders that allow for a more detailed and nuanced discussion of the drought impacts. This approach was used during this project through the convention of two focus group meetings with agricultural producers from western South Dakota to discuss the evolution of the 2016 flash drought event and the impacts that they observed on both agricultural and natural ecosystems. Insights obtained from the focus group meetings will be presented in future work. In addition, results obtained from the remaining survey questions discussing management actions taken by the producers, their data preferences when making management decisions, and other factors that influence their ability to prepare for the adverse affects of drought, are presented in a companion article by Haigh et al. (2018).

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Table 1. Summary statistics for a two-part question that asked the producers to indicate whether a tabulated set of impacts occurred on their land during 2016 and associated dates when each impact first occurred. The first two columns list the observed impact and the number of reports that provided answers for that question. The next three columns show the percentage of survey responses that indicated that a given impact was either not applicable to their operations (N/A) or did (YES) or did not (NO) occur on their land. The final column shows the mean date of occurrence for each impact.

OBSERVED IMPACT	# OF REPORTS	DID IT OCCUR?			MEAN DATE
		N/A	NO	YES	
A. Decreased topsoil moisture	329	2%	4%	94%	May 14
B. Decreased subsoil moisture	319	3%	7%	90%	May 21
C. Delayed or lack of plant emergence	317	9%	26%	65%	May 20
D. Delayed or lack of plant growth	321	2%	11%	87%	May 31
E. Plant stress (crop or pasture)	318	2%	6%	92%	Jun 16
F. Plant death (crop or pasture)	302	9%	40%	51%	June 27
G. Poor grain fill	301	46%	15%	39%	June 29
H. Deteriorating range conditions	319	5%	8%	86%	June 17
I. Decreased forage productivity	316	5%	9%	86%	June 13
J. Lowered water levels in ponds, streams, or other water sources	318	11%	9%	80%	June 6
K. Lack of water in ponds, streams, or other water sources	317	13%	16%	70%	June 16
L. Wells unable to keep up with livestock or irrigation needs	307	28%	56%	16%	June 30
M. Fire	311	23%	59%	17%	July 6
N. Infestations of insects or other pests	305	18%	57%	25%	June 15

Figure Captions

Fig. 1. Red hatched areas show individual zip codes from which completed surveys were received.

Fig. 2. (a-c) Maps showing locations where survey respondents observed decreased topsoil moisture, incipient plant stress, and lowered water levels, with the USDM map from 31 March 2016 overlaid. The black (blue) hatched areas denote zip code locations where respondents noted onset of these conditions prior to (during) the reporting period from 01-31 March. (d-h) Maps showing standardized anomalies in the Evaporative Stress Index, NLDAS topsoil moisture content, NLDAS total column soil moisture, Standardized Precipitation Index, and 2-m temperature computed using data from the previous 4 week period. All images are valid on 31 March 2016. Note that the color bar is reversed for the temperature anomalies so that red (green) colors indicate above (below) normal temperatures.

Fig. 3. Same as for Fig. 2, except all images are valid on 30 April 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during April 2016.

Fig. 4. Same as for Fig. 2, except all images are valid on 31 May 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during May2016.

Fig. 5. Same as for Fig. 2, except all images are valid on 30 June 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during June 2016.

Fig. 6. Same as for Fig. 2, except all images are valid on 31 July 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during July 2016.

Fig. 7. Same as for Fig. 2, except all images are valid on 31 August 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during August 2016.

Fig. 8. Time series showing the average conditions depicted by the USDM (black line) and by anomalies in the SPI (blue line), ESI (green line), NLDAS TS (red line), and NLDAS TC (magenta line) datasets at weekly intervals from six weeks prior to six weeks after the onset of (a) decreased TS moisture, (b) plant stress, and (c) lowered water levels as reported by the survey respondents.

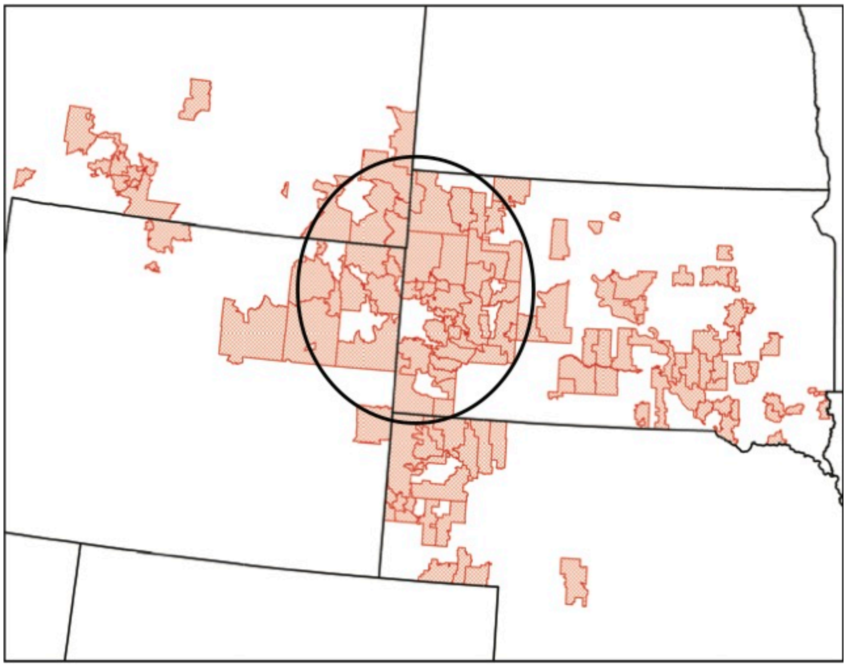


Fig. 1. Red hatched areas show individual zip codes from which completed surveys were received. The core drought region (CDR) is indicated by the black oval.

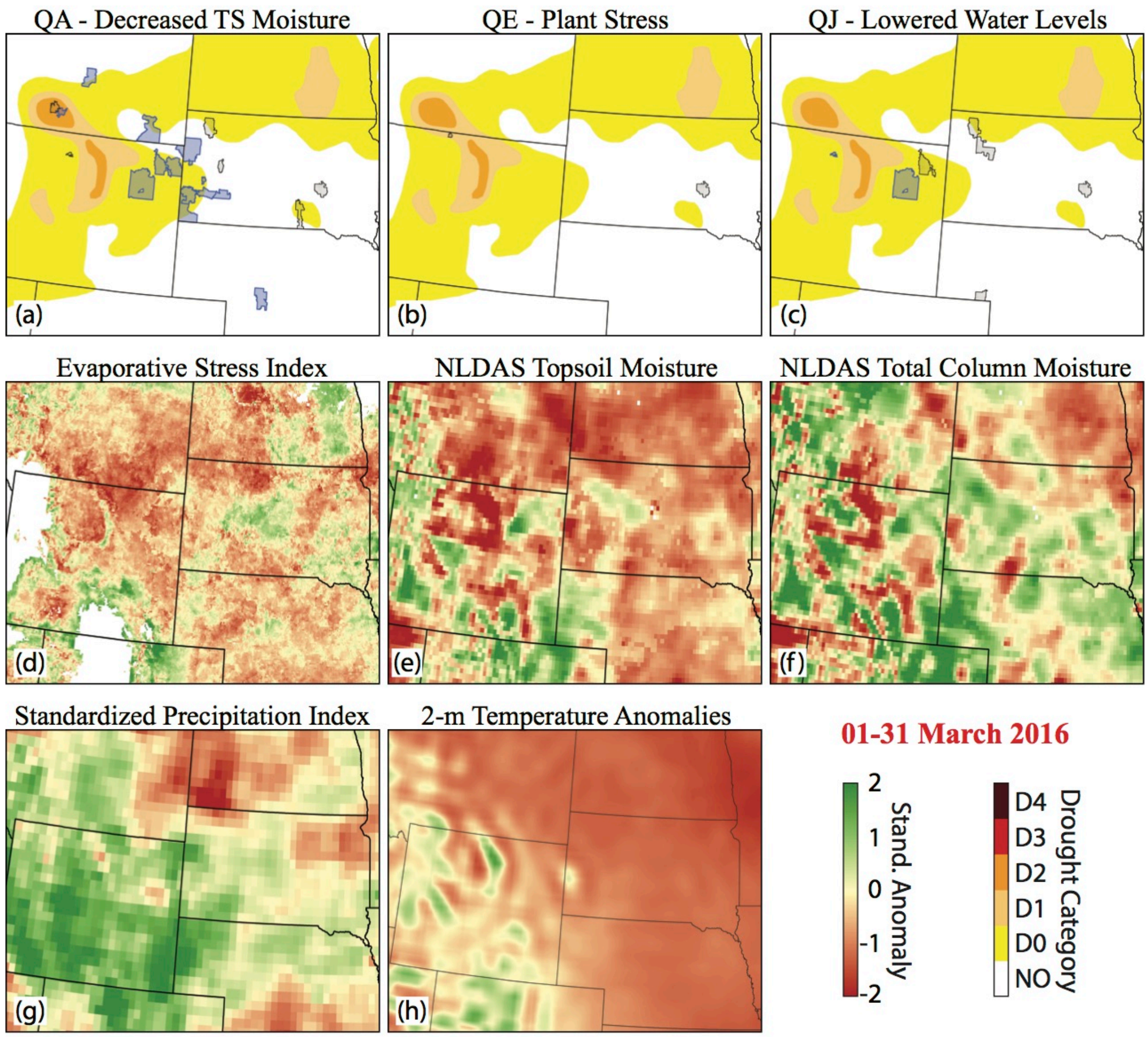
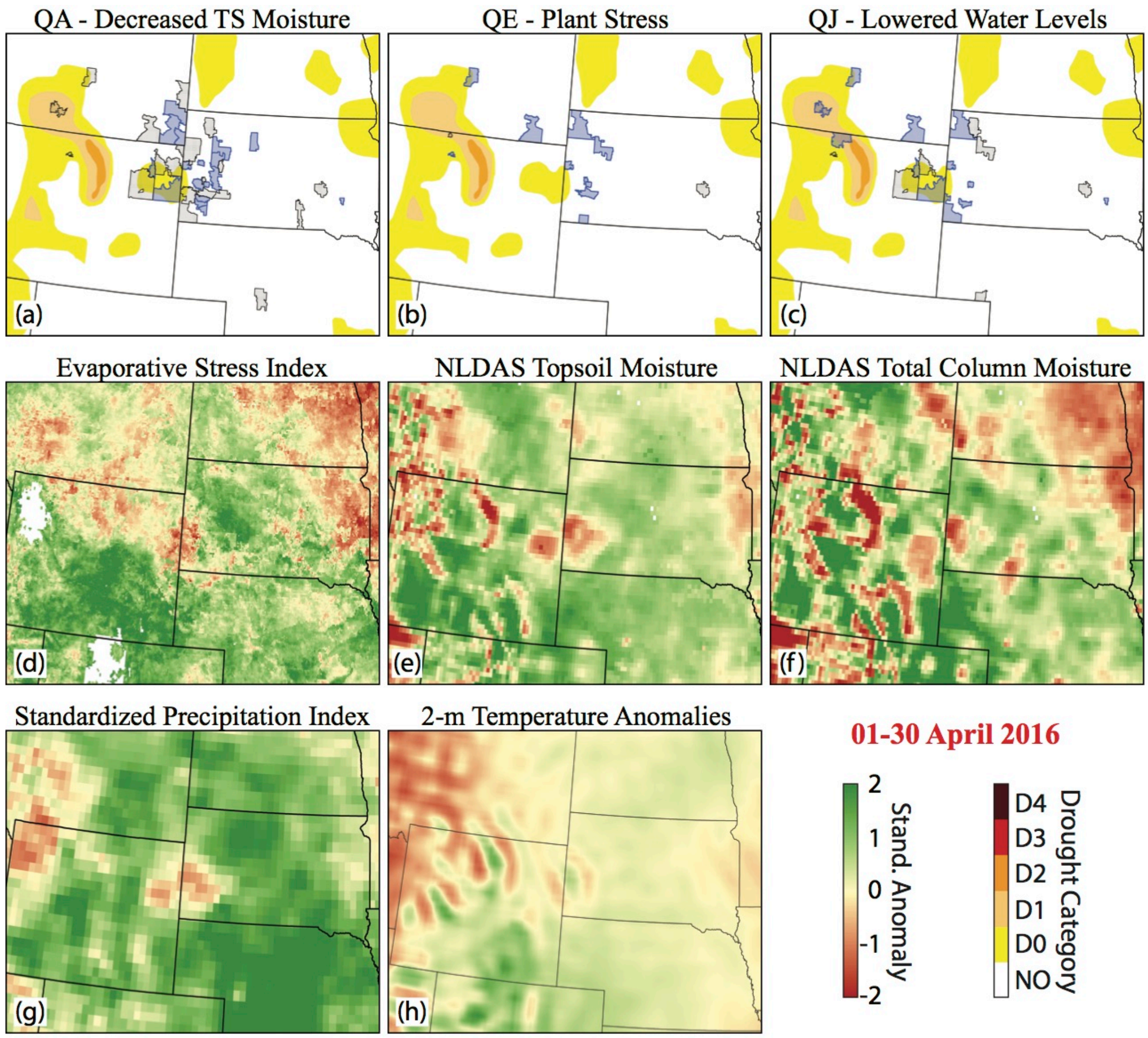


Fig. 2. (a-c) Maps showing locations where survey respondents observed decreased topsoil moisture, incipient plant stress, and lowered water levels, with the USDM map from 31 March 2016 overlaid. The black (blue) hatched areas denote zip code locations where respondents noted onset of these conditions prior to (during) the reporting period from 01-31 March. (d-h) Maps showing standardized anomalies in the Evaporative Stress Index, NLDAS topsoil moisture content, NLDAS total column soil moisture, Standardized Precipitation Index, and 2-m temperature computed using data from the previous 4 week period. All images are valid on 31 March 2016. Note that the color bar is reversed for the temperature anomalies so that red (green) colors indicate above (below) normal temperatures.



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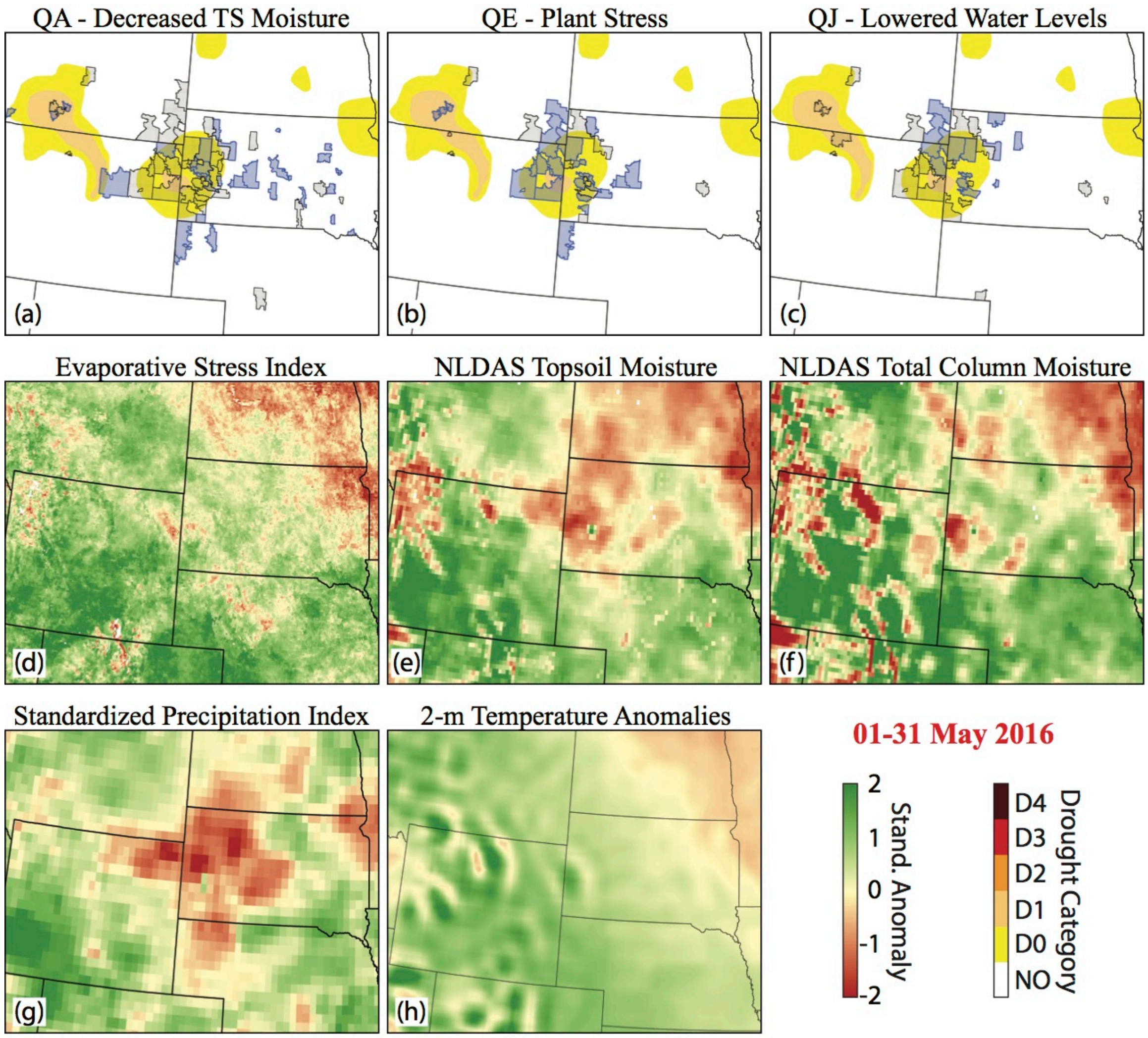

831 Fig. 4. Same as for Fig. 2, except all images are valid on 31 May 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during May2016.

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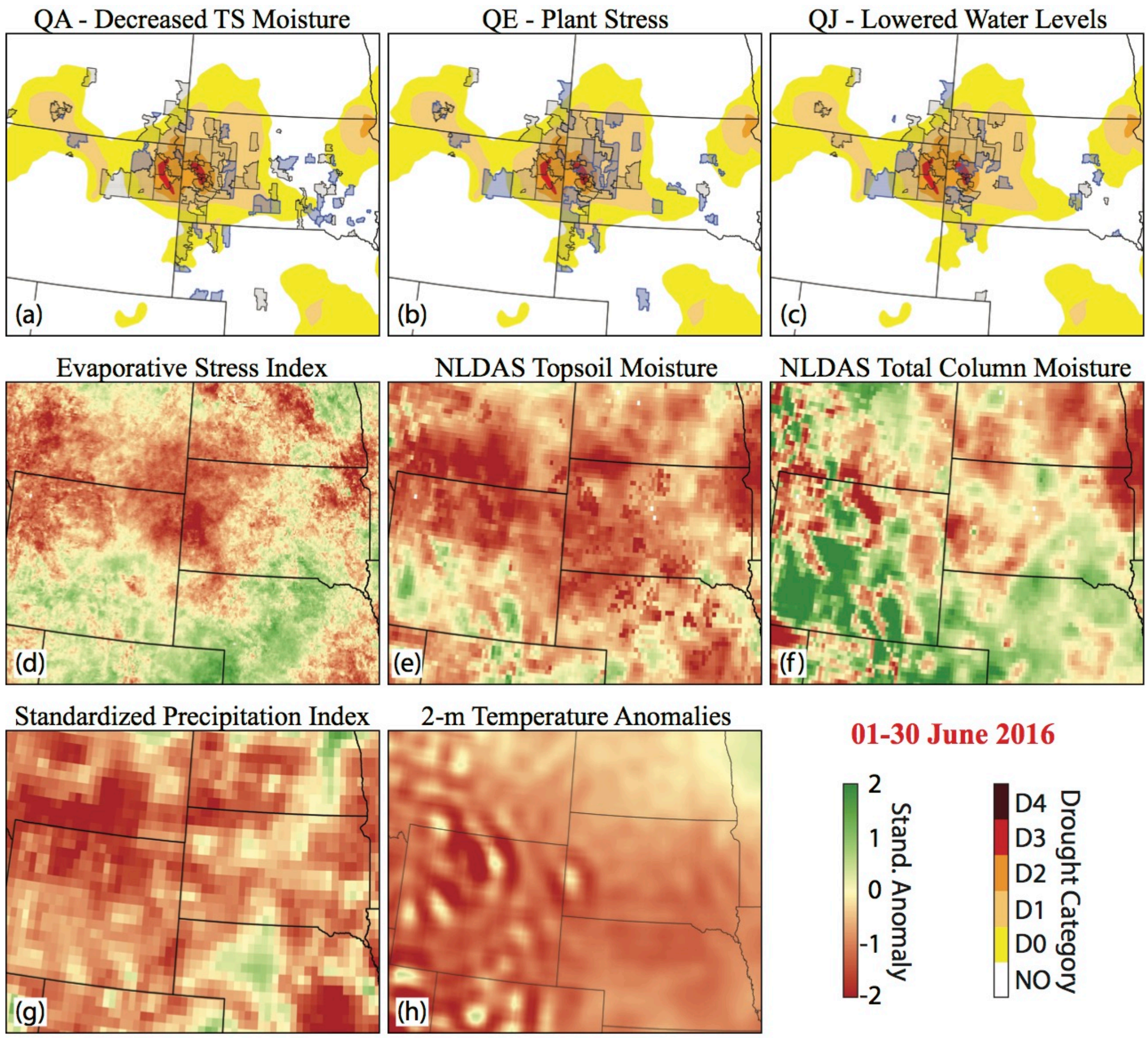
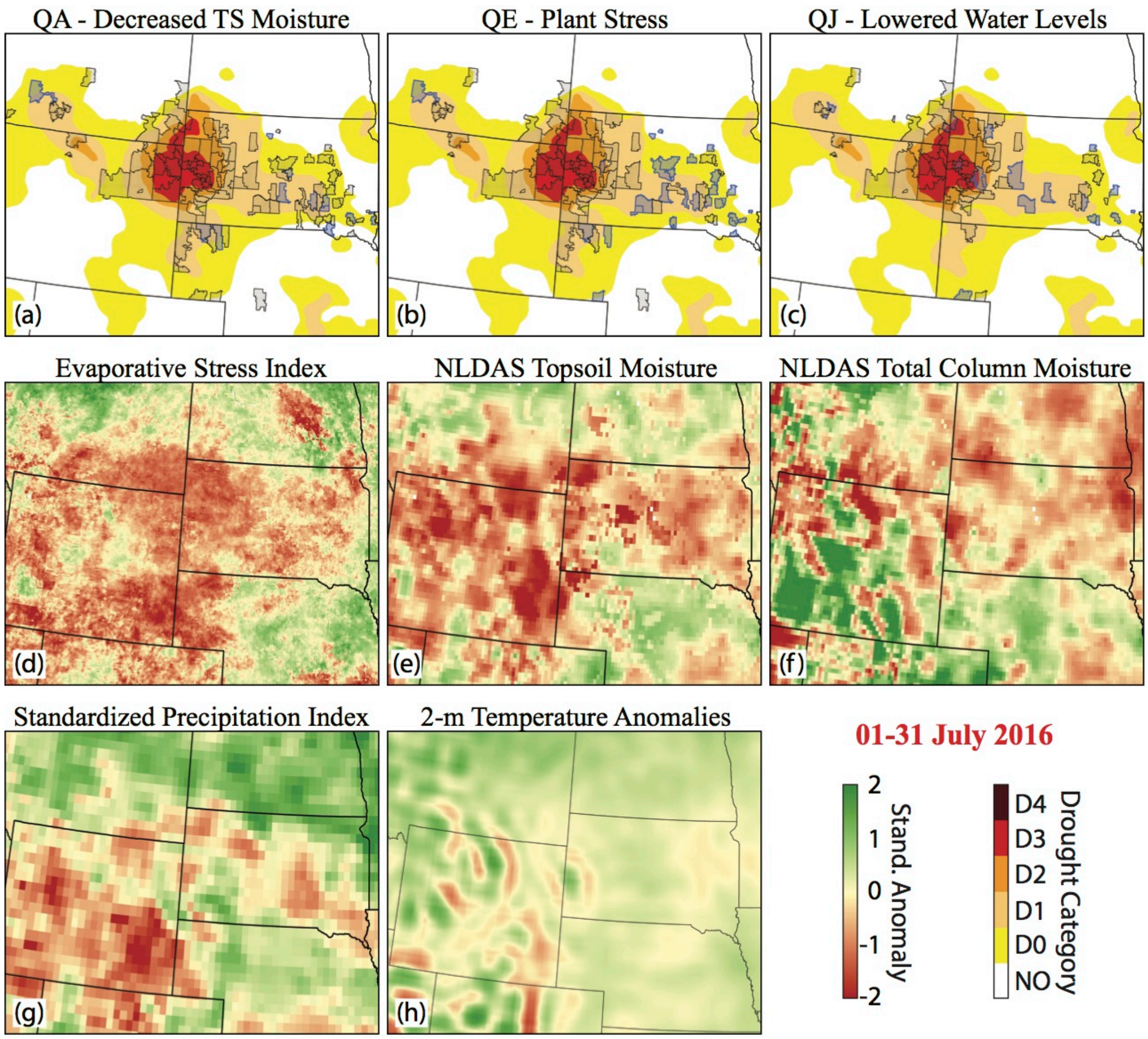
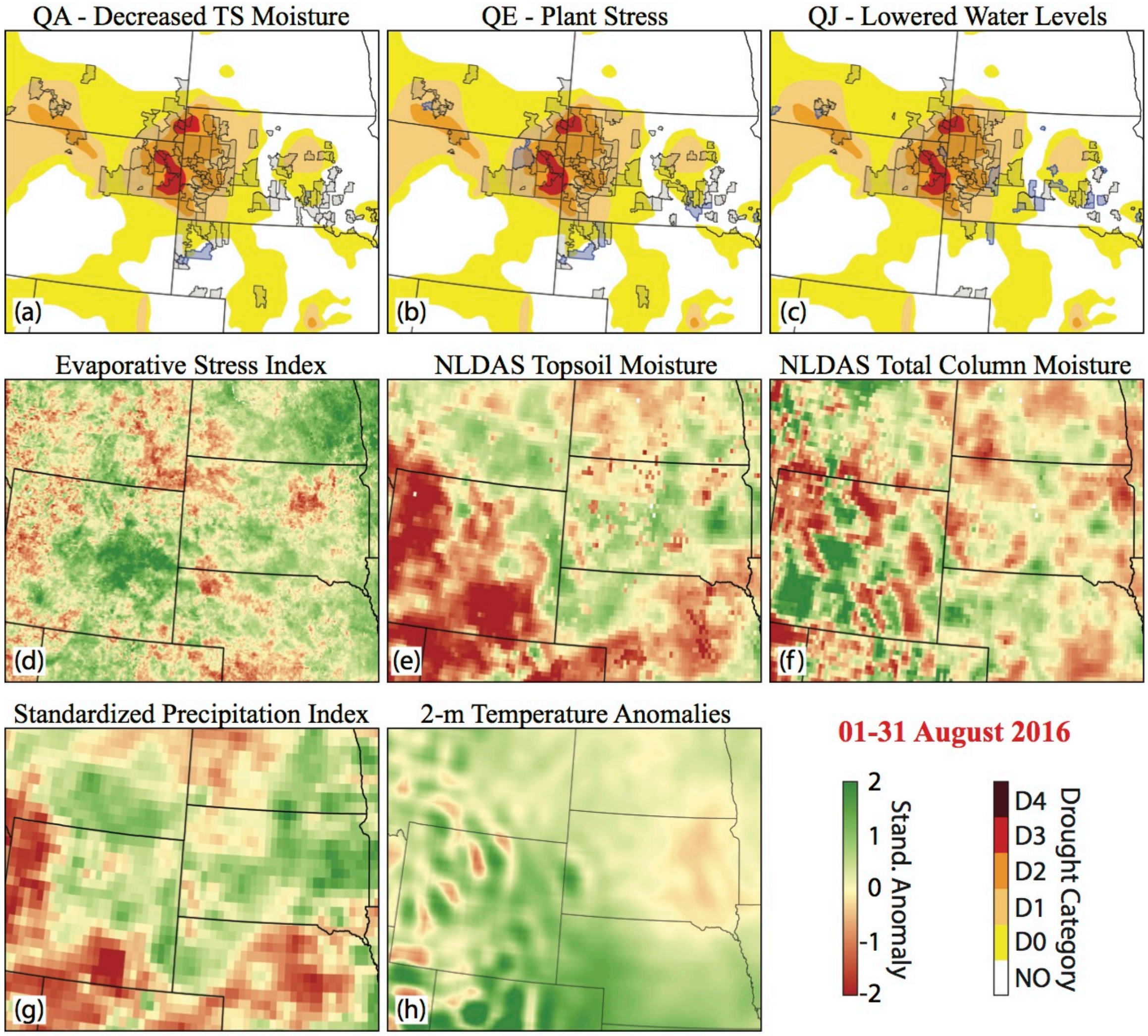


Fig. 5. Same as for Fig. 2, except all images are valid on 30 June 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during June 2016.



834 Fig. 6. Same as for Fig. 2, except all images are valid on 31 July 2016. Blue hatched areas in (a-c) denote zip codes were respondents noted onset of decreased topsoil moisture, incipient plant stress, and lowered water levels during July 2016.



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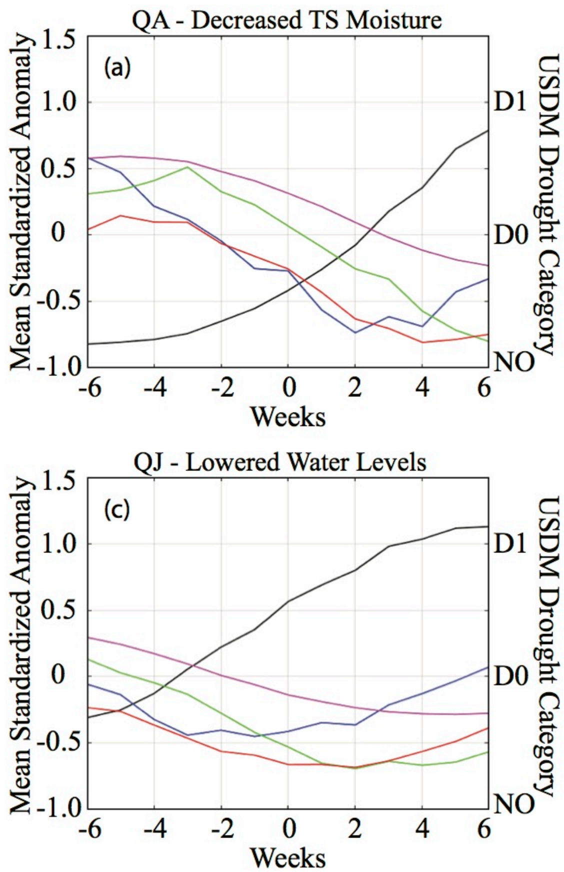

836 Fig. 8. Time series showing the average conditions depicted by the USDM (black line) and by anomalies in the SPI (blue line), ESI (green line), NLDAS TS (red line), and NLDAS TC (magenta line) datasets at weekly intervals from six weeks prior to six weeks after the onset of (a) decreased TS moisture, (b) plant stress, and (c) lowered water levels as reported by the respondents.